

## FIN FIELD EFFECT TRANSISTOR WITH SELF-ALIGNED GATE

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### DESCRIPTION

#### Field of the Invention

The present invention relates to semiconductor devices, and more particularly to a method of forming a metal oxide semiconductor field effect transistor (MOSFET) comprising thin vertical channels (i.e., the FIN) controlled by a double-gate, which involves using a trough to define the channel regions as well as the damascene gate, so as to provide a self-aligned gate. The present invention also relates to a sub-0.05  $\mu$ m double-gated/double-channel FIN MOSFET structure wherein the gate is self-aligned to the channel regions as well as the source/drain junctions.

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#### Background of the Invention

Over the past twenty-five years or so, the primary challenge of very large scale integration (VLSI) has been the integration of an ever-increasing number of MOSFET devices with high yield and reliability. This was achieved mainly in the prior art by scaling down the MOSFET channel length without excessive short-channel effects. As is known to those skilled in the art, short-channel effects are the decrease of threshold voltage  $V_t$  in short-channel devices due to two-dimensional electrostatic charge sharing between the gate and the source/drain diffusion regions.

25 To scale down MOSFET channel lengths without excessive short-channel effects, gate oxide thickness has to be reduced while increasing channel-doping concentration. However, Yan, et al., "Scaling the Si MOSFET: From bulk to SOI to bulk", IEEE Trans. Elect. Dev., Vol. 39, p. 1704, July 1992, have shown that to reduce short-channel effects for sub-0.05  $\mu$ m MOSFETs, it is important to have a backside-conducting layer present in the structure that screens the drain field away from the channel. The Yan, et al. results show that double-gated MOSFETs and MOSFETs

with a top gate and a backside ground plane are more immune to short-channel effects and hence can be scaled to shorter dimensions than conventional MOSFETs.

The structure of the prior art MOSFETs consists of a very thin vertical Si layer (FIN) 5 for the channel, with two gates, one on each side of the channel. The two gates are electrically connected so that they serve to modulate the channel. Short-channel effects are greatly suppressed in such a structure because the two gates very effectively terminate the drain field line preventing the drain potential from being felt at the source end of the channel. Consequently, the variation of the threshold voltage 10 with drain voltage and with gate length of a prior art double-gated MOSFET is much smaller than that of a conventional single-gated structure of the same channel length.

FIN MOSFETs offer potential benefits in performance as compared with conventional MOSFETs; See, for example, X. Huang, et al., IEDM Tech. Dig. 1999, p.67.

15 However, in prior art FIN MOSFETs, the gate conductor is not self-aligned to the source/drain diffusion junctions or the channel regions. Therefore, there will be a large series resistance between the channel and the heavily doped source/drain diffusion junctions.

20 To date, there are no adequate means for fabricating double-gated FIN MOSFET structures in which the gate is self-aligned to the source/drain diffusion junctions and the channels. Thus, there is a continued need for developing a new and improved method of fabricating double-gated FIN MOSFETs in which such self-alignment 25 between the gate and the source/drain diffusion junctions and channels is achieved.

#### Summary of the Invention

One object of the present invention is to provide a double-gated/double-channel FIN MOSFET structure that has sub-0.05  $\mu$ m channel lengths associated therewith.

Another object of the present invention is to provide a FIN MOSFET structure that has excellent short-channel characteristics.

A further object of the present invention is to provide a FIN MOSFET structure in 5 which the variation in threshold voltage with drain voltage and with the gate length is substantially less than that of a singled-gated MOSFET structure of the same channel length.

A yet further object of the present invention is to provide a FIN MOSFET structure 10 which has double the on-current as compared with conventional single-gated structures of the same channel length.

A still further object of the present invention is to provide a FIN MOSFET structure in 15 which the gate is self-aligned to the source/drain diffusion junctions and channel regions thereby significantly reducing the series resistance between the channels and the heavily doped source/drain diffusion junctions.

These and other objects and advantages are achieved in the present invention by 20 utilizing a method wherein a trough is employed, not only to define the regions where the channels are formed, but also to form a damascene gate. Such a method allows for the formation of a double-gated/double-channel FIN MOSFET structure in which the gate is self-aligned to the channel regions and the source/drain diffusion junctions.

One aspect of the present invention thus relates to a method of fabricating a double- 25 gated/double-channel FIN MOSFET structure having a gate region that is self-aligned with the source/drain diffusion junctions and channel regions. Specifically, the method of the present invention comprises the steps of:

(a) forming at least one patterned region atop a surface of an insulating region, said at 30 least one patterned region comprising a Si-containing layer present atop said insulating

region, a pad oxide present atop said Si-containing layer and a polish stop layer present atop said pad oxide;

5 (b) forming planarizing insulating regions abutting each patterned region, said planarizing insulating regions are formed on exposed portions of said insulating region, said planarizing insulating region being co-planar with a top surface of said polish stop layer;

10 (c) forming a hardmask on a portion of said at least one patterned region, said hardmask being used to define channel regions in said at least one patterned region;

15 (d) selectively removing a portion of said hardmask, said polish stop layer and said pad oxide layer so as to expose a portion of said Si-containing layer thereby forming channels regions and a trough;

(e) forming a gate region in said trough; and

20 (f) removing said polish stop layer and said pad oxide abutting said gate region so as to expose portions of said Si-containing layer and forming source/drain diffusion regions therein.

Another aspect of the present invention relates to a double-gated/double-channel FIN MOSFET structure which is formed utilizing the method of the present invention. Specifically, the inventive double-gated/double-channel FIN MOSFET comprises:

25 a bottom Si-containing layer;

an insulating region present atop said bottom Si-containing layer, said insulating region having at least one partial opening therein;

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a gate region formed in said at least one partial opening, said gate region comprising two regions of gate conductor that are separated from channel regions by an insulating film, said insulating film having opposite vertical surfaces adjacent to the channel regions;

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source/drain diffusion regions abutting said gate region, said source/drain diffusion regions having junctions that are self-aligned to the channels regions as well as the gate region; and

10 insulating spacers that separate the gate region and the source/drain diffusion regions formed orthogonal to said insulating film.

#### Brief Description of the Drawings

FIGS 1-11 are pictorial representations (through cross-sectional and, in some instances, top views) showing the inventive double-gated/double-channel FIN MOSFET structure through various processing steps of the present invention.

#### Detailed Description of the Invention

The present invention, which provides a method of fabricating a FIN MOSFET structure having a gate region that is self-aligned with the source/drain diffusion junctions and channel regions as well as the FIN MOSFET structure itself, will now be described in greater detail by referring to the drawings that accompany the present application. It is noted that in the accompanying drawings, like and/or corresponding elements are referred to by like reference numerals.

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Reference is first made to FIG 1 which illustrates an initial structure that is employed in the present invention in fabricating the inventive FIN MOSFET structure. Specifically, the initial structure shown in FIG 1 comprises silicon-on-insulating (SOI) material 10 which includes bottom Si-containing layer 12, insulating region 14, and 30 top Si-containing layer 16. Note that the insulating region, i.e., buried oxide region,

electrically isolates the bottom Si-containing layer from the top Si-containing layer. The term “Si-containing layer” as used herein denotes a semiconducting material that includes at least Si. Examples of such semiconducting materials, include, but are not limited to: Si, SiGe, SiGeC, SiC, polysilicon (i.e., polySi), epitaxial silicon (i.e., epi-Si), amorphous silicon (i.e., a:Si), and multilayers thereof. In one embodiment of the present invention, it is highly preferred that layers 12 and 14 of SOI material 10 are both composed of Si or polysilicon.

5 The thickness of top Si-containing layer 16 of SOI material 10 may vary, but typically, 10 the Si-containing layer has a thickness of from about 10 to about 500 nm, with a thickness of from about 50 to about 150 nm being more highly preferred. Insofar as insulating region 14 is concerned, the insulating region typically has a thickness of from about 10 to about 1000 nm, with a thickness of from about 100 to about 500 nm being more highly preferred. The thickness of bottom Si-containing layer 12 of SOI 15 material 10 is inconsequential to the present invention.

10 The SOI material shown in FIG 1 may be made from a conventional process well known in the art. For example, the SOI material may be fabricated using a thermal bonding and cutting process, or alternatively, the SOI material is fabricated using a 15 separation by ion implantation of oxygen (SIMOX) process.

20 FIG 2 illustrates the structure that is obtained after forming insulating stack 18 atop Si-containing layer 16. As shown, insulating stack 18 includes at least pad oxide layer 20 which is formed atop Si-containing layer 16 of the SOI material, and polish stop layer 25 22 which is composed of an insulating layer that has a different etch rate as compared to that of the underlying pad oxide layer. For example, the polish stop layer may be composed of a nitride such as SiN, or an oxynitride such as SiON, when the pad oxide is formed of SiO<sub>2</sub>.

Pad oxide layer 20 of insulating stack 18 is formed utilizing a conventional deposition process such as chemical vapor deposition (CVD), plasma-assisted CVD, sputtering, evaporation, chemical solution deposition, or atomic layer deposition. Alternatively, and more preferably, pad oxide layer 20 is formed utilizing a conventional thermal oxidation process. The thickness of the pad oxide layer may vary depending on the type of oxide employed as well as the process used in forming the same. Typically, however, pad oxide layer 20 has a thickness of from about 5 to about 200 nm, with a thickness of from about 10 to about 50 nm being more highly preferred.

5 The polish stop layer, which is formed utilizing a conventional deposition process including low-pressure CVD, has a thickness of from about 50 to about 500 nm, with a thickness of from about 100 to about 200 nm being more highly preferred. It is noted that the thickness of the polish stop layer may vary somewhat from the ranges reported herein.

10 15 Next, and as shown in FIG 3, at least one patterned region 24, which is comprised of patterned layers 22, 20 and 16, is formed utilizing conventional lithography and etching. The lithography step employed in forming the at least one patterned region includes the steps of forming a photoresist atop polish stop layer 22; exposing the photoresist to a pattern of radiation; and developing the pattern in the photoresist utilizing a conventional resist developer. The etching step employed in forming patterned region 24 comprises a conventional dry etching process such as reactive-ion etching (RIE), ion beam etching (IBE), plasma etching, laser ablation or any combination thereof which is capable of removing exposed regions of layers 22, 20

20 25 and 16, while stopping on insulating region 14.

Following the etching process, the patterned resist is removed providing the structure shown in FIG 3. Note that patterned region 24 defines the active area, See FIG 4B, of the inventive structure. It is also noted that although the drawings depict the formation

of only one patterned region, the present invention contemplates forming a plurality of such patterned regions on the structure.

FIGS 4A(cross-sectional view)-4B (top view) show the structure that is obtained after 5 planarizing isolation regions 26 are formed abutting patterned region 24. The planarizing isolation regions are formed by first depositing, via conventional deposition processes such as low-pressure CVD, an oxide layer such as SiO<sub>2</sub> over all exposed surfaces of the structure shown in FIG 3, and thereafter planarizing the deposited oxide layer down to the top surface of polish stop layer 22 utilizing a 10 conventional planarization process such as chemical-mechanical polishing (CMP) or grinding.

Patterned hardmask 28 is then formed atop the uppermost layer of patterned region 24, i.e., atop polish stop layer 22, utilizing a conventional deposition process such as low- 15 pressure CVD, followed by conventional lithography and etching. The resultant structure obtained after these steps of the present invention is shown, for example, in FIG 5.

Patterned hardmask 28 has a width of about 50 nm or less, with a width of from about 20 5 to about 50 nm being more highly preferred. The vertical thickness of the patterned hardmask is typically of from about 50 to about 500 nm, with a vertical thickness of from about 100 to about 200 nm being more highly preferred. Note that the patterned hardmask may be composed of the same or different oxide as planarizing insulating regions 26 and that the patterned hardmask is employed in the present invention in 25 defining channel regions 35.

Next, and as illustrated in FIGS 6A (cross-sectional)-6B (top view), patterned photoresist 30 having at least one opening 32 exposing a portion of patterned hardmask 28 is then formed over the structure shown in FIG 5. Specifically, patterned 30 resist 30 having opening 32 is formed utilizing conventional lithography as described

hereinabove. It is noted that this step of the present invention defines the regions where the gate conductor will be subsequently formed. At this point of the present invention, any polish stop layer that is adjacent to the channel region, not protected by patterned hardmask 28, is removed utilizing a selective RIE process.

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To define the structure shown in FIGS 6A-6B, that structure is subjected to selective etching processes that are capable of removing the exposed portions of patterned hardmask 28 as well as the underlying portions of polish stop layer 22 stopping on a portion of pad oxide layer 20. The resulting structure formed after these selective 10 etching processes is shown, for example, in FIGS 6A (cross-sectional)-6B (top view). The selective etching processes used at this point of the present invention include the use of a first etching process that selectively removes oxide as compared to nitride, and a second etching process which selectively removes nitride as compared to oxide.

15 The first etching process may comprise the use of a fluorine-containing gas or plasma having an etch selectivity of at least about 20:1, whereas the second etching process may include the use of Cl-based chemistries having an etch selectivity of at least about 10:1. Note that the second etching process defines channel regions 35 of the inventive structure.

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FIGS 7A-7B show the resultant structure after conducting the selective etching processes which provide troughs 34 in the isolation regions for the gate conductors. The etch is a fluorine-base chemistry that etches  $\text{SiO}_2$  selective to  $\text{Si}_3\text{N}_4$ .

25 This selective etching processes also removes the exposed portions of pad oxide 20 from the regions adjacent to the channel (i.e., those regions not protected by hardmask 22). See, for example, in FIG 7B. The structure shown in FIG 8 is obtained by utilizing a third selective etching process in which a chlorine-containing etching gas or plasma having an etch selectivity of at least about 10:1 is employed. This etches the 30 exposed Si adjacent to hardmask 22, leaving a vertical Si FIN that defines the channel

regions. Following the third selective etching process, the resist is removed utilizing a conventional stripping process well known to those skilled in the art. Note that portions of hardmask 28 are also removed at this point of the present invention.

- 5 After stripping the resist from the structure, a sacrificial oxide layer (not shown) is formed by conventional thermal growing processes on the exposed wall portions of the trough, the sacrificial oxide is thereafter removed using a chemical etchant such as HF, and an oxide layer (not shown) is then formed on the exposed, and now cleaned, tough sidewalls.

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FIGS 9A(cross-section)-9B(top view) show the resultant structure that is obtained after insulating spacers 36 and gate dielectric 38 are formed in the trough.

Specifically, the insulating spacers are formed utilizing a conventional deposition process such as low-pressure CVD and etching, e.g., RIE wherein a fluorine-based plasma is employed. Note that over-etching is typically employed so as to remove spacers from the channel regions. The thickness of hardmask 22 should be greater than the thickness of Si layer 16 so that spacers remain adjacent to the source/drain diffusion regions, but not on the channel regions. Insulating spacers 36 are comprised of an oxide, a nitride, an oxynitride or any combination and multilayer thereof.

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Next, a sacrificial oxide layer (not shown) is formed, as described above, then the sacrificial oxide layer is removed, as described above, and thereafter gate dielectric 38 is formed by utilizing a conventional deposition process. Alternatively, a conventional thermal growing process may be used in forming the gate dielectric.

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The gate dielectric formed at this point of the present invention may include an oxide, a nitride, an oxynitride or any combination thereof including multilayers. A preferred gate dielectric employed in the present invention is an oxynitride such as SiON.

The thickness of the gate dielectric formed at this point of the present invention may vary depending on the gate dielectric material as well as the process used in forming the same. Typically, gate dielectric 38 has an effective electrical thickness assuming the dielectric constant is equal to that of  $\text{SiO}_2$  of from about 1 to about 5 nm, with a 5 thickness of from about 1 to about 2 nm being more highly preferred.

Following the formation of the insulating spacers and gate dielectric, gate conductor 40 is formed over the channel and the trough regions shown in FIGS 9A-9B. The resultant structure after formation of gate conductor 40 is shown in FIG 10. Note that 10 the top surface of the gate conductive material is co-planar with the top surface of isolation regions 26. Specifically, the gate conductor material is deposited utilizing a conventional deposition process including low-pressure CVD and thereafter a conventional planarization process such as CMP is employed.

15 The gate conductor material used at this point of the present invention includes any conductive material which is typically employed in MOSFET devices. For example, the gate conductive material employed in the present invention may be comprised of polysilicon, amorphous Si, elemental metals that are conductive, alloys of conductive elemental metals, silicides or nitrides of conductive elemental metals and multilayers 20 thereof, e.g., a conductive gate stack including, for example, a layer of polysilicon and a conductive elemental metal. When a conductive gate stack is employed, a conventional diffusion barrier such as Ta, Ti, TaN or TiN may be formed between the conductive layers.

25 Polish stop layer 22 and pad oxide layer 20 are then removed from the structure utilizing conventional wet etching processes or a chemical down stream dry etching process well known in the art so as to expose portions of underlying Si-containing layer 16. The exposed portions of the Si-containing layer are then subjecting to a ion implantation process wherein an ion (n- or p-type) is implanted using an ion dose on 30 the order of about  $1\text{E}15$  atoms/cm<sup>2</sup> or greater. Following ion implantation, the doped

regions of the Si-containing layer are annealed at a temperature of about 700°C or greater so as to form activated source/drain diffusion regions 42 that have junction regions which are self-aligned to the gate edges.

5 The resultant structure obtained using the inventive process is shown, for example, in FIG 11A (cross-sectional) and B (top view). Specifically, the inventive structure includes bottom Si-containing layer 12, an insulating region (14 and 26) present atop the bottom Si-containing layer. Insulating region (14+26) having at least one partial opening 50 therein. A gate region 70 formed in the partial opening, said gate region 10 comprising two regions of gate conductor 40 that are separated from channel regions 35 by insulating film, i.e., gate dielectric, 38 which surrounds a portion of Si-containing layer 16, said insulating film having opposite vertical surfaces adjacent to channel regions 35; source/drain diffusion regions 42 abutting said gate region, said source/drain diffusion regions having junctions that are self-aligned to the channels 15 regions as well as the gate region; and insulating spacers 36 that separate gate region 70 and source/drain diffusion regions 42 formed orthogonal to insulating film 38.

In addition to the processing steps mentioned above, the present invention also 20 contemplates other conventional MOSFET processing steps that are well known in the art. For example, the present invention also contemplates forming salicide regions atop the source/drain diffusion regions, and forming contacts and/or interconnects over the salicide regions.

25 While the present invention has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in forms and details may be made without departing from the scope and spirit of the present invention. It is therefore intended that the present invention not be limited to the exact forms and details described and illustrated, but fall within the scope of the appended claims.